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Advances in *r*-Process Nucleosynthesis

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Abstract

During the last several decades, there have been a number of advances in understanding the rapid neutron-capture process (i.e., the *r*-process). These advances include large quantities of high-resolution spectroscopic abundance data of neutron-capture elements, improved astrophysical models, and increasingly more precise nuclear and atomic physics data. The elemental abundances of the heavy neutron-capture elements, from Ba through the third *r*-process peak, in low-metallicity ([Fe/H] $\lesssim$ –2.5) Galactic halo stars are consistent with the scaled (i.e., relative) solar system *r*-process abundance distribution. These abundance comparisons suggest that for elements with Z $\geq$ 56 the *r*-process is robust—appearing to operate in a relatively consistent manner over the history of the Galaxy—and place stringent constraints on *r*-process models. While not yet identified, neutron-rich ejecta outside of the core in a collapsing (Type II, Ib) supernova continues to be a promising site for the *r*-process. Neutron star binary mergers might also be a possible alternative site. Abundance comparisons of lighter *n*-capture elements in halo stars show variations with the scaled solar *r*-process curve and might suggest either multiple *r*-process sites, or, at least, different synthesis conditions in the same astrophysical site. Constraints on *r*-process models and clues to the progenitors of the halo stars—the earliest generations of Galactic stars—are also provided by the star-to-star abundance scatter of [Eu/Fe] at low metallicities in the early Galaxy. Finally, abundance observations of long-lived radioactive elements (such as Th and U) produced in the *r*-process can be used to determine the chronometric ages of the oldest stars, placing constraints on the lower limit age estimates of the Galaxy and the Universe.

1.1 Introduction

Most of the heavy elements (here, Z $>$ 30) in the solar system are formed in neutron-capture (*n*-capture) processes, either the slow (*s*-) or rapid (*r*-) process. Our understanding of the distinction between these two processes follows from the pioneering work of Cameron (1957) and Burbidge et al. (1957). In the *s*-process the relative lifetime for neutron captures (τ_n) is much longer than for electron (β) decays (τ_β). As a result, the *n*-capture path in the *s*-process is near the so-called valley of beta stability, and the properties of nuclei involved in this nucleosynthesis are, in great part, experimentally accessible. The situation is quite different in the *r*-process where $\tau_n \ll \tau_\beta$. Thus, the *r*-process path occurs in a very

neutron-rich regime far from stability, making experimental measurements of those nuclei very difficult, if not impossible.

In this review we focus on advances in our understanding—still very incomplete—of the *r*-process. We note there have been a number of earlier reviews, including those by Hillebrandt (1978), Mathews & Cowan (1990), Cowan, Thielemann, & Truran (1991a), Meyer (1994), Truran et al. (2002), and Sneden & Cowan (2003). We employ and emphasize the observed stellar *n*-capture abundances in our discussion of the *r*-process. These abundances, particularly in low-metal (i.e., low iron, [Fe/H], abundance) stars, provide direct clues to the natures of the *r*-process and *s*-process formation sites. In addition, the abundances of the *n*-capture elements and related chemical evolution studies have also provided important information concerning the *r*-process, specifically in relation to early Galactic nucleosynthesis and star formation history (see reviews of Galactic chemical evolution by, e.g., Wheeler, Sneden, & Truran 1989, McWilliam 1997, and Truran et al. 2002). We also note, and discuss briefly, the importance of certain long-lived radioactive elements, such as thorium and uranium, produced entirely in the *r*-process. The abundance levels of these nuclear chronometers in the most metal-poor halo stars can provide direct age determinations, and hence set lower limits on Galactic and cosmological age estimates (see, e.g., Cowan, Thielemann, & Truran 1991b).

1.2 Neutron-capture Abundances

In this section we examine the abundances of the elements, concentrating on those produced in neutron-capture processes. We show in Figure 1.1 the solar system abundances based upon the compilation of Grevesse & Sauval (1998). Earlier compilations include those of Anders & Ebihara (1982), Cameron (1982a), and Anders & Grevesse (1989). We also note the very recent solar system abundance determinations of Lodders (2003). These solar system abundances can in many ways be treated as "cosmic" and are frequently employed for stellar abundance comparisons.

We highlight in Figure 1.1 the abundances of the neutron-capture elements in solar system material. As is well known, these elements above iron are synthesized predominantly by, and are the sum of individual isotopic contributions from, the *s*- and the *r*-process. The deconvolution of the solar system material into the *s*-process and *r*-process has traditionally relied upon reproducing the "σ N" curve (i.e., the product of the *n*-capture cross section and *s*-process abundance). This "classical approach" to the *s*-process is empirical and, by definition, model independent. Subtracting these *s*-process isotopic contributions from the solar abundances determines the residual *r*-process contributions. Early deconvolutions of solar system material into respective *s*- and *r*-process contributions were performed by Clayton et al. (1961), Seeger, Fowler, & Clayton (1965), and Cameron (1982b). We show in Figure 1.2 a more recent such deconvolution based upon *n*-capture cross section measurements (Käppeler, Beer, & Wisshak 1989; Wisshak, Voss, & Käppeler 1996). In addition to this classical approach, more sophisticated models, based upon *s*-process nucleosynthesis in low-mass AGB stars, have been developed recently (Arlandini et al. 1999). Comparing the solar system elemental *r*-process abundance predictions obtained from these model calculations (Arlandini et al. 1999) with the classical approach (Burris et al. 2000) indicates good agreement between each other and with observed stellar abundances (Cowan et al. 2002; Sneden et al. 2003). We also note in Figure 1.2 that the *s*- and *r*-process solar system abundance distributions indicate that not just individual isotopes but entire elements were synthesized

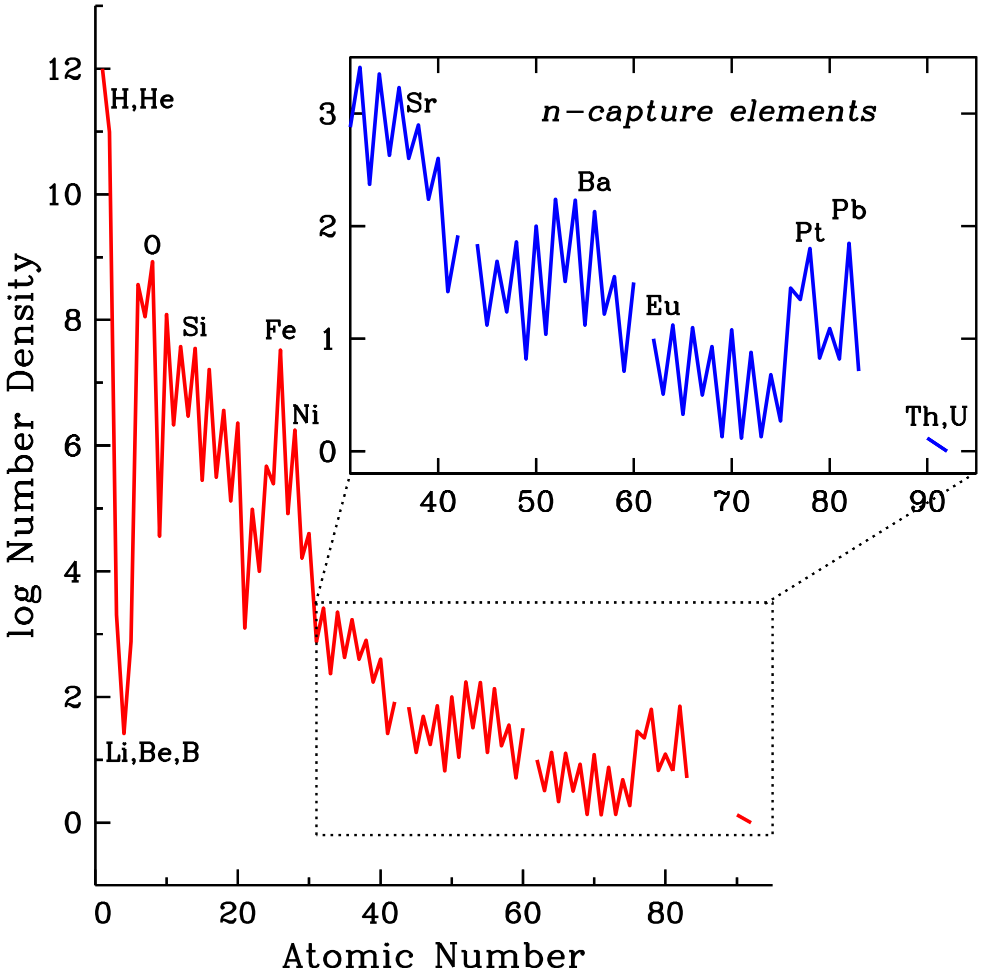

Fig. 1.1. Abundances of elements in the Sun and in solar system material. This abundance set is normalized by convention to log N(H) = 12. The main figure shows the entire set of stable and long-lived radioactive elements, while the inset is restricted to only those (neutron-capture) elements with Z $>$ 30.

primarily in the *s*-process (e.g., Sr, Ba) or the *r*-process (e.g., Eu, Pt) in solar system material. These solar *s*-process, and corresponding *r*-process, elemental abundance distributions have been tabulated in, for example, Sneden et al. (1996) and Burris et al. (2000).

1.3 Stellar Abundance Observations

Many of the new advances in understanding the *r*-process have come from stellar abundance observations, and we highlight some of those critical new results in this section.

1.3.1 Metal-poor Stars

Various research groups over the last several decades have been employing the observed abundance distributions in metal-poor ([Fe/H] $<$ –1) Galactic halo stars—bright

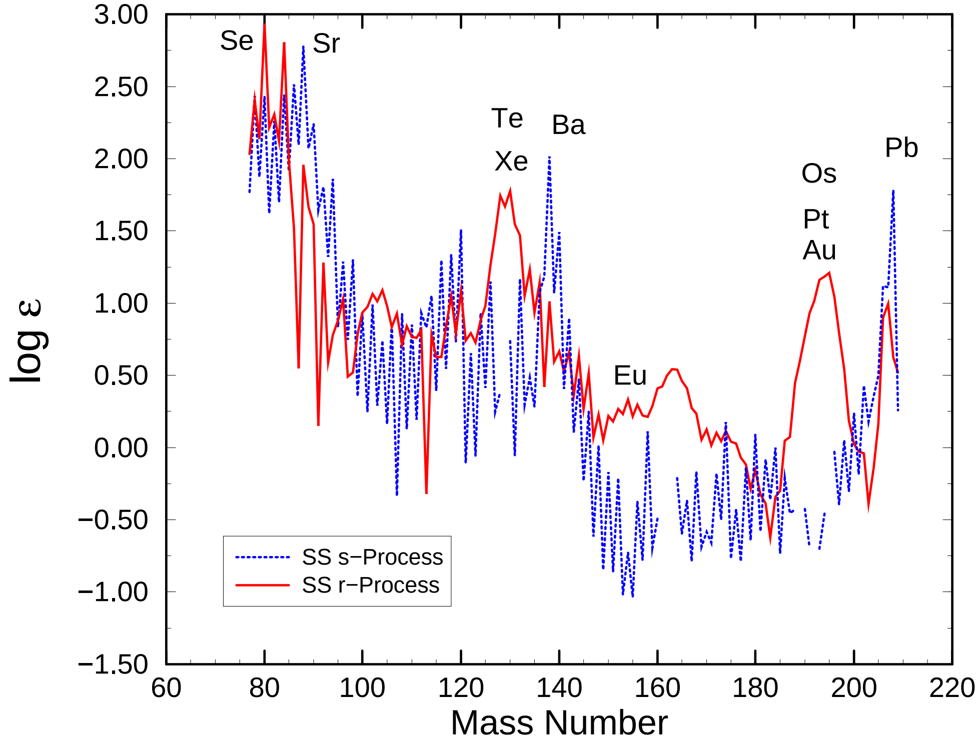

Fig. 1.2. The *s*-process (dotted line) and *r*-process (solid line) abundances in solar system matter, based upon the work by Käppeler et al. (1989). The total solar system abundances for the heavy elements are from Anders & Grevesse (1989).

giants with relatively "uncrowded" spectra—to try to identify, and to understand, the signatures of the *r*- and the *s*-process (see, e.g., Spite & Spite 1978; Sneden & Parthasarathy 1983; Sneden & Pilachowski 1985; Gilroy et al. 1988; Gratton & Sneden 1994; Cowan et al. 1995; McWilliam et al. 1995; Ryan, Norris, & Beers 1996; Sneden et al. 1996; Burris et al. 2000; Johnson & Bolte 2001; Hill et al. 2002). These studies have all suggested the dominance of the *r*-process in the oldest and most metal-poor Galactic halo stars. We show in Figure 1.3 the abundances of *n*-capture elements in CS 22892–052 ([Fe/H] = –3.1) compared with scaled solar system *r*-process (Burris et al. 2000, solid line) and *s*-process (Burris et al. 2000, dashed line) abundance distributions (Sneden et al. 2003). It is very clear that the *n*-capture element abundances in this star are entirely consistent with the relative solar system *r*-process abundance distribution. (The stellar abundances are also well fit with the solar system *r*-process predictions of Arlandini et al. 1999.) It is also clear that *s*-process nucleosynthesis was not responsible for forming the elements observed in this star, at least in anything resembling solar proportions.

Detailed abundance distributions, with more than a few *n*-capture elements, have been obtained for relatively few cases—probably fewer than 20 of the metal-poor halo stars. This picture has been changing in the last few years, however, with new comprehensive abun-

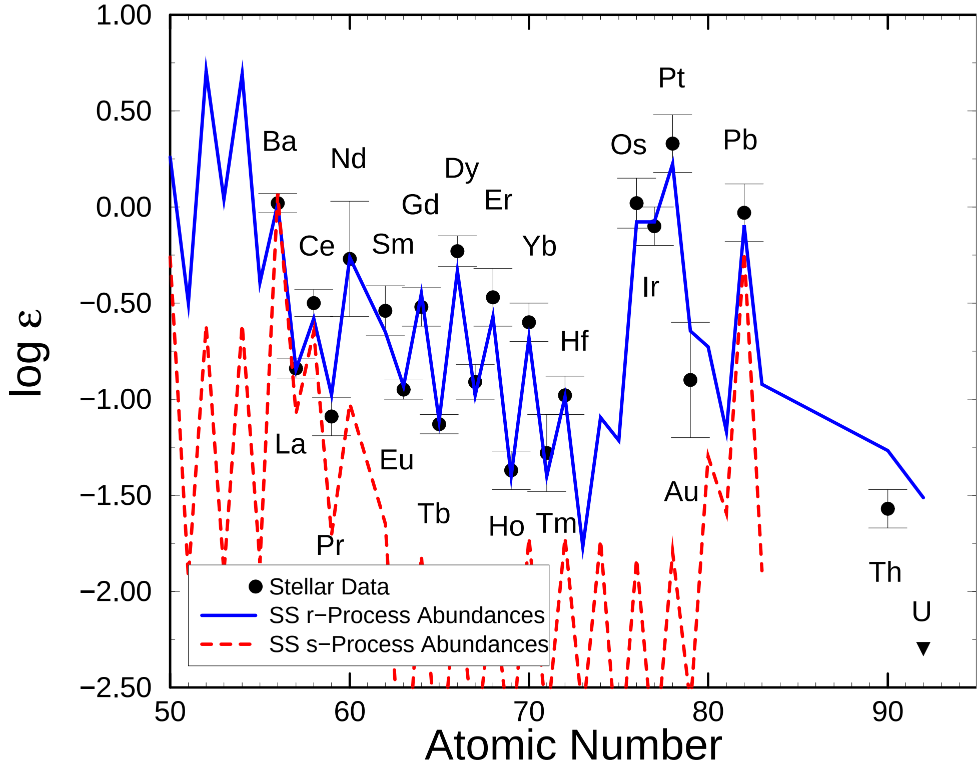

Fig. 1.3. The heavy element abundance pattern for CS 22892–052, normalized to Ba, is compared with the scaled solar system *r*-process (solid line) and *s*-process (dashed line) abundance distributions.

dance studies of the stars CS 22892–052 (Sneden et al. 1996, 2000a, 2003), HD 115444 (Westin et al. 2000), BD +17°3248 (Cowan et al. 2002), and CS 31082–001 (Hill et al. 2002). We show in Figure 1.4 relative abundance distributions in those four stars, again compared with a scaled solar system *r*-process distribution (solid lines). Particularly noteworthy has been: (1) the increasing accessibility of elements in the third *r*-process peak, typically only available with observations in the UV with the *Hubble Space Telescope*; and (2) the increasingly precise abundance determinations, resulting in great part from marked improvements in the atomic physics data (see, e.g., Lawler, Bonvallet, & Sneden 2001; Den Hartog et al. 2003, and references therein). In fact, advancements in the atomic physics input have eliminated more and more discrepancies between observed metal-poor stellar abundances and solar *r*-process abundance predictions. Further improvements in individual elemental abundance determinations might be employed to constrain the various theoretical predictions of the actual solar system *r*-process abundances.

Figure 1.4 makes clear that for all four of these *r*-process-rich stars, the elemental abundances, from Ba through the third *r*-process peak, are consistent with relative solar *r*-process proportions. This suggests that for elements with Z $\geq$ 56 the *r*-process is very robust, appearing to operate in a relatively consistent manner over the history of the Galaxy. This

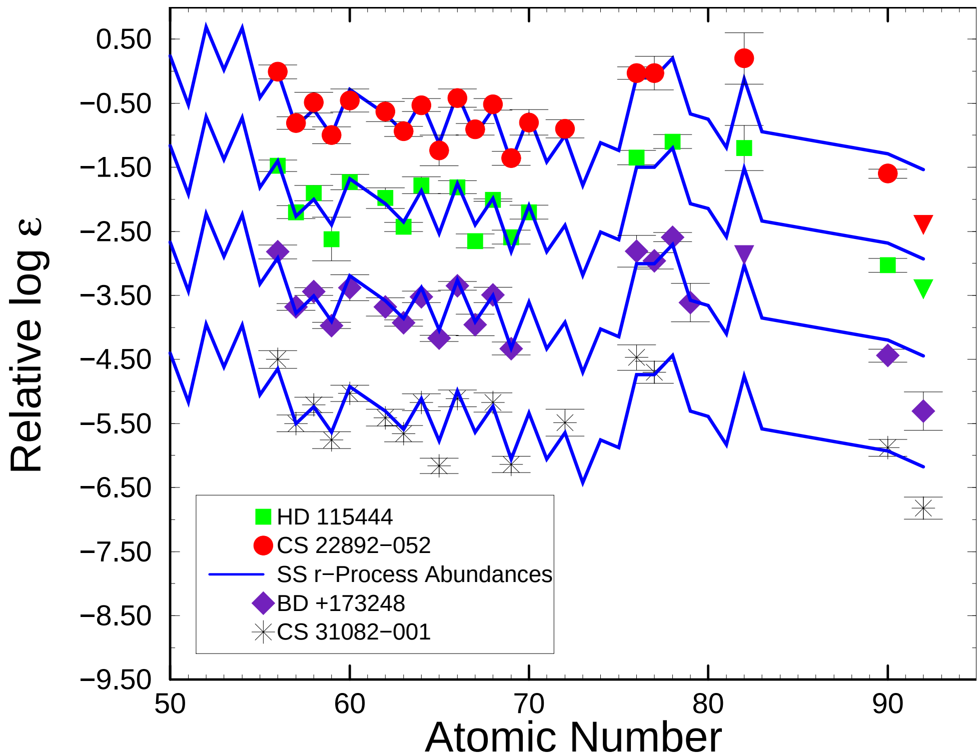

Fig. 1.4. The heavy element abundance patterns for the four stars CS 22892–052, HD 155444, BD +17°3248, and CS 31082–001 are compared with the scaled solar system *r*-process abundance distribution (solid line) (see Westin et al. 2000; Cowan et al. 2002; Hill et al. 2002; Sneden et al. 2003). The absolute abundances have been shifted for all stars except CS 22892–052 for display purposes. Upper limits are indicated by inverted triangles.

might imply a similar range of conditions (both astrophysical and nuclear) for the operation of the *r*-process (Freiburghaus et al. 1999a), and perhaps even a narrow range of masses for supernovae sites of the *r*-process (e.g., Mathews, Bazan, & Cowan 1992; Wheeler, Cowan, & Hillenbrandt 1998; Ishimaru & Wanajo 1999).

1.3.2 Isotopic Abundances

While there have been a continuing number of observations of elements in the metal-poor stars, isotopic abundance studies have been relatively rare. This has been predominantly due to observational difficulties—isotopic wavelength shifts for transitions of most all *n*-capture elements are small compared to the thermal and turbulent line widths in stellar spectra. Recently, Sneden et al. (2002) and Aoki et al. (2003) have determined europium isotopic abundance fractions in four very metal-poor, *r*-process-rich stars: CS 22892–052, HD 115444, BD +17°3248, and CS 31082–001. The abundance fractions for Eu in these stars are in excellent agreement with each other and with their values in the solar system: fr(^{151}Eu) $\simeq$ fr(^{153}Eu) $\simeq$ 0.5. Additional Eu stellar abundance studies that

demonstrate this same solar system *r*-process agreement have been reported (Ivans 2003, private communication). These isotopic abundance observations support earlier studies that indicate that stellar elemental abundances for Z $\geq$ 56 match very closely those of a scaled solar system *r*-process abundance distribution. With only two isotopes, perhaps it is not totally surprising that the Eu abundance fractions in the metal-poor halo stars are the same as in the solar system. It does suggest, though, that the solar abundances are cosmic, in some sense, and that the *r*-process (for the heavier *n*-capture elements) is robust over the lifetime of the Galaxy. Nevertheless, a more definitive test would be an isotopic analysis of the element Ba with many more isotopes than Eu. Lambert & Allende-Prieto (2002) have done such an analysis in another metal-poor star, HD 140283, and find that the isotopic fractions of Ba are also consistent with the solar *r*-process values. Additional stellar isotopic abundance studies will be necessary to strengthen and extend these findings.

1.4 The *r*-Process

Although the *r*-process has been studied for many years, the actual site for this nucleosynthesis has not been identified. Further complicating this search is the possibility of more than one such site. Nevertheless, there has been much progress in our understanding of the astrophysical models and the related nuclear physics of the *r*-process.

1.4.1 Astrophysical Sites and Models

The nature of the *r*-process requires high neutron number densities on short time scales, indicative of explosive environments. The early work of Burbidge et al. (1957) suggested that the neutron-rich ejecta outside of the core in a collapsing (Type II, Ib) supernova was the likely site for the *r*-process. Nevertheless, the detailed physics of core-collapse supernovae were poorly known at that time, to say nothing of the lack of computational tools. These hindrances prevented definitive identifications on the nature of the *r*-process and led to the consideration of other possible sites, including the shocked helium and carbon zones of exploding supernovae and jets and bubbles of neutron-rich material ejected from the collapsing core (see Cowan et al. 1991a, and references therein). Inhomogeneous Big Bang cosmological models were even studied as possible sites (Rauscher et al. 1994).

Advances in understanding supernova physics, particularly neutrino interactions, led to new promising *r*-process scenarios, such as the high-entropy neutrino wind in supernovae (Takahashi, Witti, & Janka 1994; Woosley et al. 1994; Qian & Woosley 1996; Wanajo et al. 2001, 2002; Terasawa et al. 2002). There have been some problems, however, with these models in obtaining the required entropies and in some inadequate abundance predictions (see, e.g., Meyer, McLaughlin, & Fuller 1998; Freiburghaus, Rosswog, & Thielemann 1999b; Thompson, Burrows, & Myer 2001; but see also Thompson 2003). (See Thielemann et al. 2002 for a general review of nucleosynthesis in supernovae and the related model uncertainties.) While much emphasis has been placed on determining the physics in "delayed" models, "prompt" supernova explosion scenarios have not been abandoned as a possible site for the *r*-process (see, e.g., Wheeler et al. 1998; Sumiyoshi et al. 2001; Wanajo et al. 2003). It has also been argued that not all core-collapse supernovae are responsible for *r*-process synthesis. In particular there have been a number of studies that suggest only low-mass ($\lesssim$) 11 $M_\odot$supernovae are likely sites (Mathews & Cowan 1990; Mathews et al. 1992; Wheeler et al. 1998; Ishimaru & Wanajo 1999; Wanajo et al. 2003; but see also Wasserburg & Qian 2000 or Cameron 2001).

While most of the attention in studying the *r*-process has focused on supernovae, there has been some consideration of neutron star binaries, which have an abundance of neutron-rich material. Early studies suggested that the tidal interaction between a neutron star and a black hole, or a second neutron star, might be a possible astrophysical site for this nucleosynthesis (see, e.g., Lattimer et al. 1977). Despite encouraging recent studies by Rosswog et al. (1999) and Freiburghaus et al. (1999a), however, there are questions about whether the frequency of these events and the amount of *r*-process ejecta per merger are consistent with observational constraints (Qian 2000).

Accompanying the advances in these more sophisticated astrophysical models has been a concomitant improvement in our understanding of the nuclear physics involved in the *r*-process - particularly more reliable nuclear information about the very neutron-rich nuclei. The *r*-process occurs far from stability, and, thus, in the past there has been little reliable nuclear data available. Recently, however, there have been an increasing amount of experimental determinations of critical nuclear data, including half-lives and neutron-pairing energies (see, e.g., Pfeiffer, Kratz, & Möller 2002; Möller, Pfeiffer, & Kratz 2003). In addition to these new nuclear data, there have been recent advances in theoretical prescriptions for very neutron-rich nuclear data (see, e.g., Chen et al. 1995; Pearson, Nayak, & Goriely 1996; Möller, Nix, & Kratz 1997). In particular, these developments include nuclear mass formulae that are more reliable and physically predictive for nuclei far from stability—especially crucial for chronometer studies—for example, such mass models as ETFSI-Q and HFBCS-1 (see Schatz et al. 2002 for discussion and additional references therein). The combination of more nuclear data and advances in theoretical mass models has led to increasingly more reliable descriptions for very neutron-rich nuclei, necessary for a better understanding of the *r*-process (see also Pfeiffer et al. 2001 for further discussion)

1.4.2 Two *r*-Processes?

The observations (discussed above) demonstrate that the heavier (Ba and above, Z $\geq$ 56, or A $\gtrsim$ 130–140) neutron-capture elements, particularly in *r*-process-rich stars, are consistent with a scaled solar system *r*-process curve. Until very recently, however, there has been relatively little data for elements between Zr and Ba. We show in Figure 1.5 the total abundance summary of the elements in CS 22892–052. A total of 58 elements (53 detections and 5 upper limits) have been observed in this star, which appears to be the most of any other star except the Sun at the time (Sneden et al. 2003). The dashed line in the figure indicates the iron abundance ([Fe/H] = –3.1) in this star. It is clear from the abundances of the heavy *n*-capture elements why this star has been so well studied—[Eu/Fe], for example, is enhanced by approximately a factor of 45 above the iron abundance level. It is also seen in this figure that the abundances of the light *n*-capture elements in the little-explored element regime of Z = 40–50 mostly lie below those of the heavy *n*-capture elements.

This difference is seen in more detail in Figure 1.6, where the abundances in CS 22892–052 (Sneden et al. 2003) are compared with two predictions for solar system *r*-process abundances, by Burris et al. (2000; top panel) and Arlandini et al. (1999; bottom panel). The dotted line in each panel indicates the unweighted mean difference for elements in the range 56 $\leq$ Z $\leq$ 79. It is clear that the stellar abundance data are well fit by both of these distributions for Z$\geq$ 56, confirming earlier such results (as discussed above and shown in Figs. 1.3 and 1.4). The data, however, seem to indicate that some of the lighter *n*-capture elements from Z = 40–50 (for example Ag and Mo) are not consistent with (i.e., in general fall below)

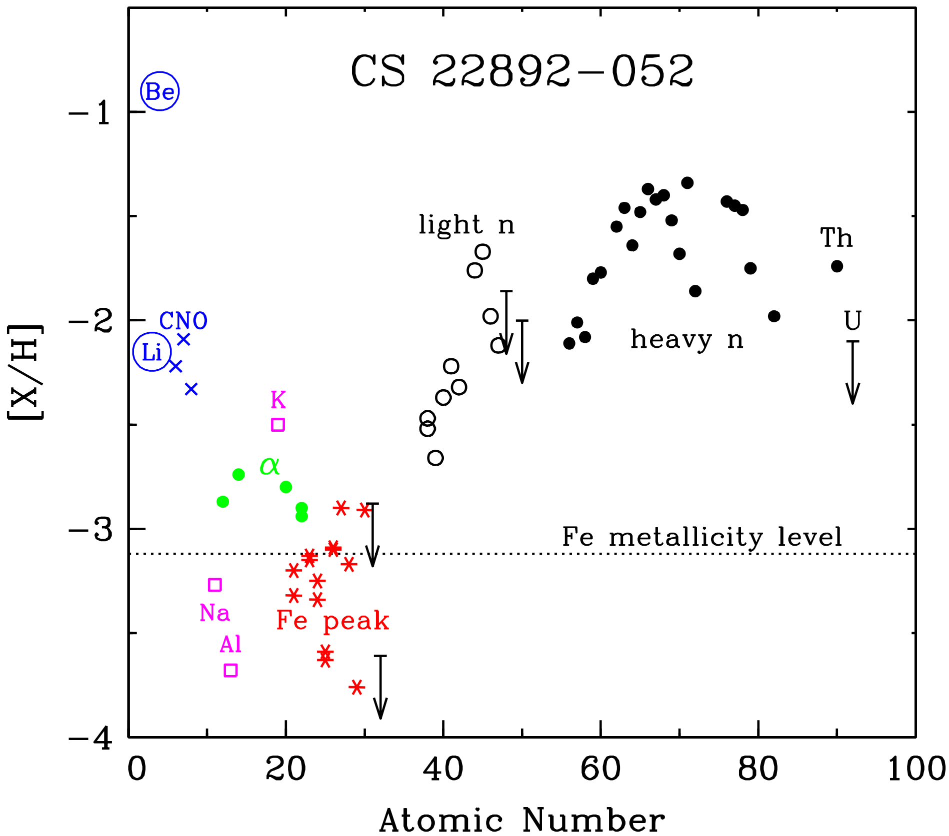

Fig. 1.5. Total abundance pattern in CS 22892–052 with respect to solar system values. The dashed line represents the iron abundance (i.e., the metallicity of the star). Upper limits are denoted by downward-pointing arrows. Li and Be are displaced from their actual abundance values for display purposes.

those same scaled *r*-process curves that fit the heavy *n*-capture elements. There are exceptions, with the abundances of Nb and Rh seemingly consistent with the scaled solar system *r*-process curve, but on average these lighter elements do seem to have been synthesized at a lower abundance level than the heavier *n*-capture elements.

There are several possible explanations for the differences in the abundance data for the lighter and heavier *n*-capture elements. These observations might support earlier suggestions of two *r*-processes based upon solar system meteoritic (isotopic) data (Wasserburg, Busso & Gallino 1996). It has been suggested, for example, that perhaps, analogously to the *s*-process, the lighter elements might be synthesized in a "weak" *r*-process with the heavier elements synthesized in a more robust "strong" (or "main") *r*-process (Truran et al. 2002). Thus, the helium zones of exploding supernovae, have been suggested as possible second *r*-process sites that might be responsible for the synthesis of nuclei with A $\lesssim$ 130–140 (Truran

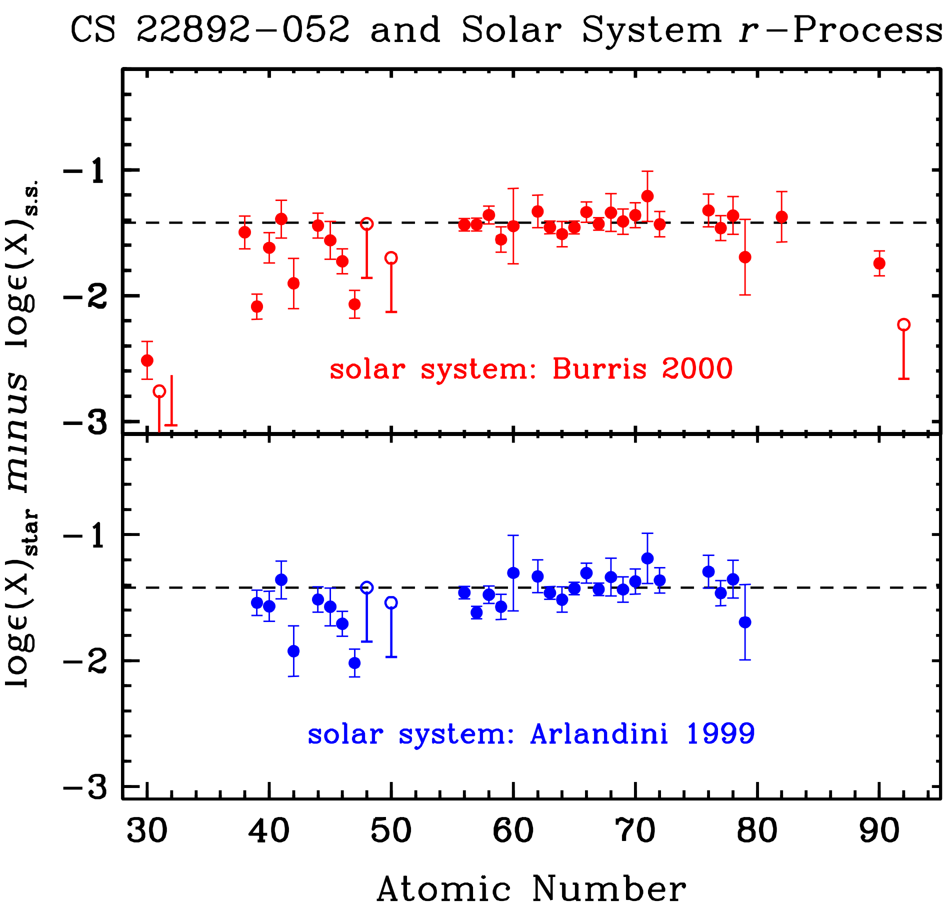

Fig. 1.6. Differences between CS 22892–052 abundances and two scaled solar system abundance distributions, after Sneden et al. (2003). The dotted line in each panel indicates the unweighted mean difference for elements in the range $56 \leq Z \leq 79$. In the top panel the abundance differences relative to those of Burris et al. (2000; their Table 5) are shown. Upper limits are indicated by open circles, except for Ge (Z = 32), because its upper limit lies below the lower limit boundary of the plot. In the bottom panel the abundance differences are relative to those of Arlandini et al. (1999), who tabulated *n*-capture abundances only for the atomic number range $39 \leq Z \leq 81$.

& Cowan 2000). Or the two sites might come from supernovae of a different mass range or frequency (Wasserburg & Qian 2000), or perhaps a combination of supernova and neutron star binaries (Truran et al. 2002). Alternative interpretations have suggested that the entire abundance distribution could be synthesized in a single core-collapse supernova (Sneden et al. 2000a; Cameron 2001). We note, however, that only a few (three) stars have detailed abundance distributions that include data in this Z = 40–50 element domain. Crawford et al. (1998), however, detected silver in four halo stars, and Sr, Pd, and Ag abundances for a

sample of metal-poor stars have been reported by Johnson & Bolte (2002). Further detailed spectroscopic studies, in conjunction with additional theoretical efforts, will be necessary to determine any differences in the nature and history of the synthesis of the lighter and heavier *r*-process elements.

1.5 *r*-Process Abundance Scatter in the Galaxy

A number of observational and theoretical studies have demonstrated that at the earliest times in the Galaxy the *r*-process was primarily responsible for *n*-capture element formation, even for elements (such as Ba) that are formed primarily in the *s*-process in solar system material (Spite & Spite 1978; Truran 1981; Sneden & Parthasarathy 1983; Sneden & Pilachowski 1985; Gilroy et al. 1988; Gratton & Sneden 1994; McWilliam et al. 1995; Cowan et al. 1995; Sneden et al. 1996; Ryan et al. 1996). The presence of these *r*-process elements in the very oldest stars in our Galaxy strongly suggests the astrophysical *r*-process site is short-lived. Thus, the first stars, the progenitors of the halo stars, were likely massive and evolved quickly, synthesized the *r*-process elements and ejected them into the interstellar medium before the formation of the currently observed stars. In contrast, the primary site for *s*-process nucleosynthesis is low- or intermediate-mass stars (i.e., $M \simeq 0.8 - 8\ M_{\odot}$) with long evolutionary time scales (Busso, Gallino, & Wasserburg 1999). Thus, these stars would not have had time to have synthesized the first elements in the Galaxy.

Further clues about the nature of the *r*-process are found in examining the abundance scatter of *n*-capture elements in the early Galaxy. This trend was first noted by Gilroy et al. (1988) and then studied in more detail by Burris et al. (2000). We show in Figure 1.7 [Eu/Fe] as a function of metallicity for a number of halo and disk stars from Sneden & Cowan (2003) (see also Truran et al. 2002 and references therein). The increasing level of star-to-star scatter of [Eu/Fe] with decreasing metallicity, particularly at values below [Fe/H] $\approx$ –2.0, suggests an early, chemically unmixed and inhomogeneous Galaxy. These data also suggest that not all early stars are sites for the formation of both *r*-process nuclei and iron. Instead, this scatter is consistent with the view that only a small fraction (2%–10%) of the massive stars that produce iron also yield *r*-process elements (Truran et al. 2002). Various theoretical models to explain this abundance scatter have been proposed by, for example, Qian & Wasserburg (2001) and Fields, Truran, & Cowan (2002). Observations to help differentiate between these models and provide new insight into the nature and site of *r*-process nucleosynthesis in the early Galaxy are ongoing (Norris 2003).

1.6 *r*-Process Chronometers

The abundances of certain radioactive *n*-capture elements, known as chronometers, can be utilized to obtain age determinations for the oldest stars, which in turn put lower limits on age estimates for the Galaxy and the Universe. Thorium, with a half-life of 14 Gy, in ratio to Nd (Butcher 1987) and to Eu (Pagel 1989) was suggested as such a chronometer. Th/Eu is a preferred ratio—both are *r*-process elements and any possible evolutionary effects of the predominantly *s*-process Nd are avoided. The detection of thorium in very metal-poor stars was pioneered by François, Spite, & Spite (1993), and since then has been observed in a number of these stars. Chronometric ages, based upon the Th/Eu ratios, have typically fallen in the range of 11–15 Gyr for the observed stars (e.g., Sneden et al. 1996; Cowan et al. 1997, 1999; Pfeiffer, Kratz, & Thielemann 1997; Sneden et al. 2000a, 2003; Westin et al. 2000; Johnson & Bolte 2001; Cowan et al. 2002). Th/Eu ratios have also been determined

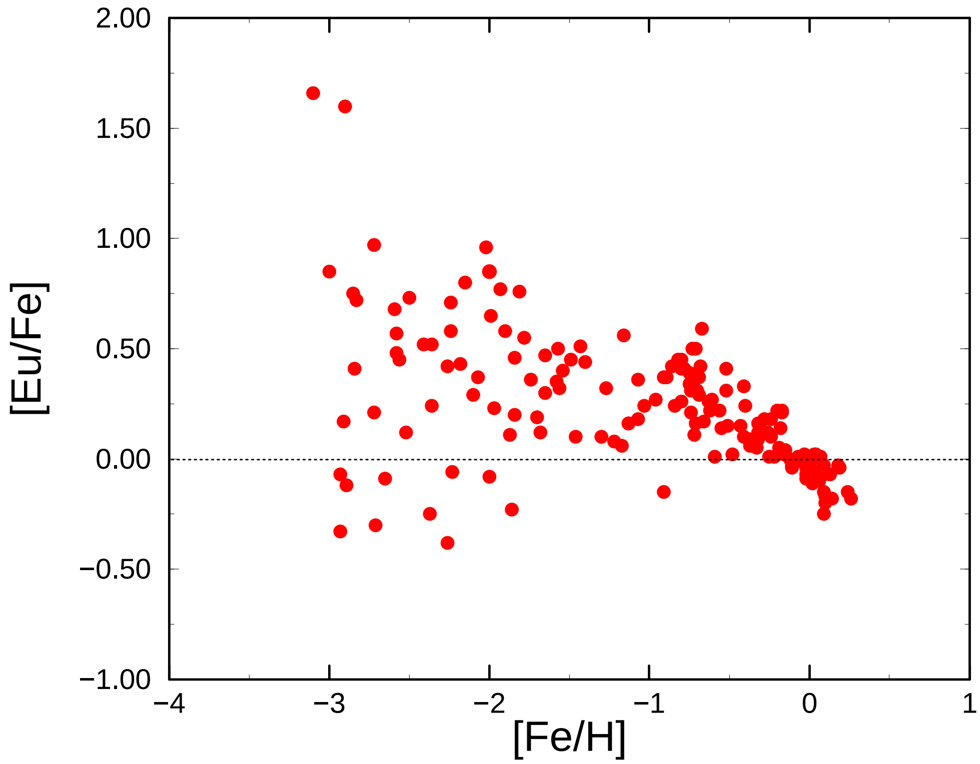

Fig. 1.7. Abundance scatter of [Eu/Fe] versus metallicity for samples of halo and disk stars, after Sneden & Cowan (2003).

for several giants in the globular cluster M 15 (Sneden et al. 2000b), who estimated their average, and hence the cluster, age at 14 ± 4 Gyr.

These age estimates all typically have errors $\sim \pm 3-4$ Gyr resulting from both observational and nuclear uncertainties. In particular the chronometric age estimates depend sensitively upon the initial predicted values of Th/Eu and hence on the nuclear mass formulae and *r*-process models employed in making those determinations. We show, for example, in Figure 1.8 theoretical predictions for these ratios in comparison with recent abundance determinations in CS 22892–052 (Sneden et al. 2003). Utilizing the ETFSI-Q mass formula, the top panel shows predictions from Cowan et al. (1999), while the bottom panel shows a newer prediction, constrained by some recent experimental data (Sneden et al. 2003). These differences lead to age uncertainties of $\sim$2 Gyr, while very different mass formulae lead to a wider range of initial abundance ratios and correspondingly wider range in age estimates (see Cowan et al. 1999; Truran et al. 2002). The large separation in nuclear mass number between Th and Eu might also exacerbate uncertainties in these initial predictions (see, e.g., Goriely & Arnould 2001). Thus, it would be preferable to obtain abundances of stable elements nearer in mass number to thorium (third *r*-process peak elements, for example), or, even better, to obtain two long-lived chronometers such as Th and U.

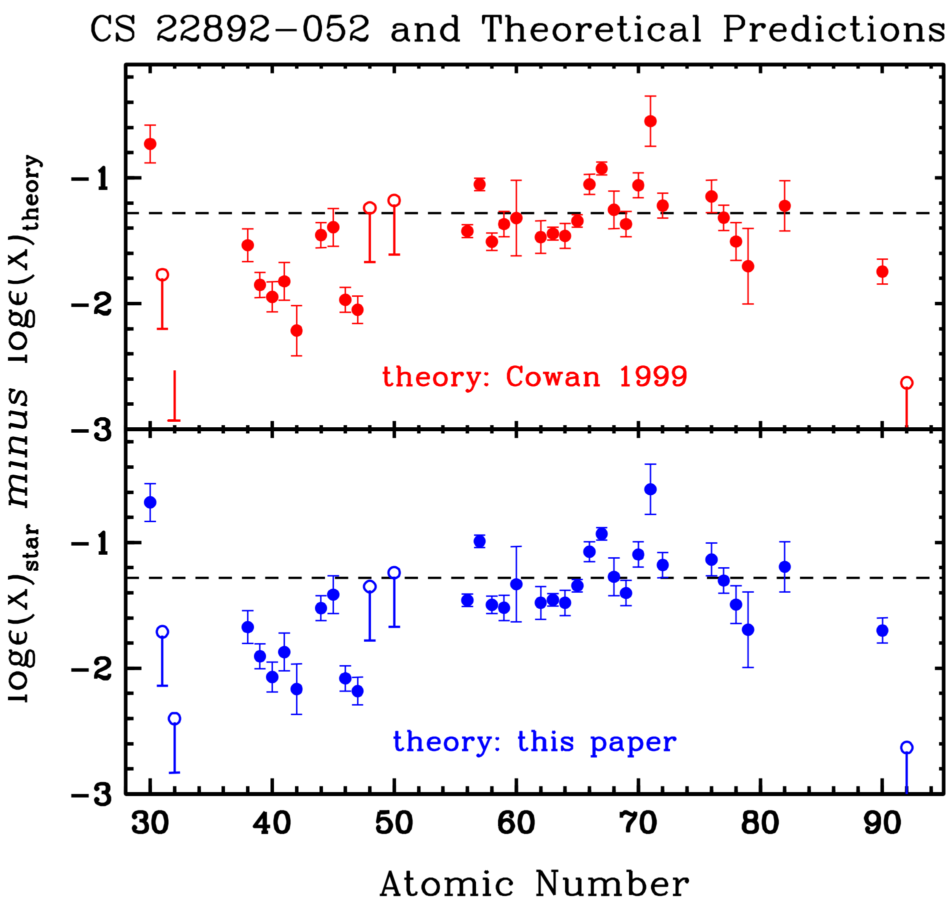

Fig. 1.8. Differences between CS 22892–052 abundances and two scaled *r*-process theoretical predictions, after Sneden et al. (2003). The top panel shows the abundance differences relative to those of Cowan et al. (1999), while the bottom panel differences are relative to Sneden et al. (2003).

Uranium was first detected in any halo star by Cayrel et al. (2001), who initially estimated the age of CS 31082–001 at 12.5 $\pm$ 3 Gyr. More refined abundance determinations (Hill et al. 2002) and recent theoretical studies have suggested an age of 15.5 $\pm$ 3.2 Gyr (Schatz et al. 2002). We note a fundamental difference in the abundance pattern of this star in comparison with several other metal-poor halo stars shown in Figure 1.4. Both Th and U are enhanced greatly with respect to the other stable elements, including Eu, in CS 31082–001. Thus, employing Th/Eu as a chronometer gives an unrealistic, even a negative, age in this case (Hill et al. 2002; Schatz et al. 2002; see also Cayrel 2003 for a more complete discussion of chronometers in this star). Interestingly, another tentative U detection has been recently reported in the metal-poor halo star BD +17°3248 (see Fig. 1.4), and in this case, Th/U and Th/Eu give comparable age values. It is not clear yet why CS 31082–001, with its

very large overabundances of Th and U, is so different, but it clearly suggests that Th/U is a more reliable chronometer than Th/Eu—certainly it is in this star. Unfortunately, it may be difficult to detect uranium in many halo stars; note the nondetection of this element in CS 22892−052 (Sneden et al. 2003). Additional such detections of U, as well as continually improving nuclear descriptions of the very neutron-rich nuclei participating in the *r*-process, will be necessary to strengthen this technique and reduce the age uncertainties.

1.7 Summary and Conclusions

A wealth of stellar abundance data has been assembled during the last several decades. These high-resolution spectroscopic studies of low-metallicity halo stars—accompanied by significant new experimental atomic physics data—have provided significant clues about the nature of the *r*-process and, at the same time, have imposed strong constraints on astrophysical and nuclear model calculations. The heavy *n*-capture abundances, from $Z \geq 56$, appear to be consistent with the relative solar system *r*-process abundance fractions, at least for the *r*-process-rich stars. This consistency suggests a similar mechanism, or well-constrained astrophysical conditions, for the operation of the *r*-process over many billions of years. While there are less data available of the lighter *n*-capture elements, the abundances of those elements appear to be not consistent—on average lower—with the same scaled solar system *r*-process distribution that fits the heavier *n*–capture elements. Various explanations have been offered to explain this difference between the lighter and heavier *n*-capture abundance distributions: the possibility of two astrophysical sites for the *r*-process (e.g., different masses or frequencies of supernovae, or a combination of supernovae and neutron star binary mergers), or models with different conditions in the same single core-collapse supernova. At this time, however, it is not clear what the exact causes are for the apparent differences in the abundance distributions of the lighter and heavier *n*-capture elements.

While the actual site for the *r*-process has not been definitively identified, there have been many advances in our understanding of the astrophysical models and the related nuclear physics of this nucleosynthesis. Core-collapse supernovae remain a promising site for the origin of the *r*-process nuclei. Much of the recent focus has been on obtaining more physically reliable supernova models (e.g., including an improved treatment of neutrino processes). Neutron star binary mergers, with improved treatments of their evolution and coalescence, have also been studied and can still be considered a possible site for the *r*-process. Accompanying these improved astrophysical models has been more experimental nuclear data and more reliable theoretical prescriptions for neutron-rich nuclei far from stability.

The abundance patterns in the oldest Galactic halo stars have also provided additional new insights into the origins and sites of the *r*-process. First, the elemental and isotopic abundances in the oldest halo stars are consistent with an *r*-process-only origin at the earliest times in the history of the Galaxy. These results suggest that the *r*-process sites in the earliest stellar generations, the progenitors of the halo stars, were rapidly evolving—ejecting *r*-process-rich material into the interstellar medium long before the major onset of Galactic *s*-process nucleosynthesis from low- and intermediate-mass stars. In addition, the star-to-star abundance scatter (e.g., [Eu/Fe]) observed in the lowest metallicity (i.e., oldest) Galactic halo stars places strong constraints on models of nucleosynthesis and suggests that not all early stars were sites for the formation of both *r*-process nuclei and iron. Further, this abundance scatter suggests an early chemically unmixed Galaxy.

The detection of the long-lived chronometers thorium, and now uranium, in some of the

metal-poor halo stars has allowed for the radioactive dating of the oldest stars. This technique depends sensitively upon the observed stellar values and the theoretical predictions of the initial abundance ratios (Th/Eu, Th/U, etc.) of elements synthesized in the *r*-process. While there have been significant advances in nuclear physics, both in experiment and theory, we still need to better define the properties of very *n*-rich (radioactive) nuclei. These improvements will be necessary to better understand the origin and nature of the *r*-process and to reduce chronometric age uncertainties—strengthening the radioactive dating technique, and providing more precise age estimates for the Galaxy and the Universe.

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